JOURNAL OF AIRCRAFT
Vol. 29, No. 5, Sept.–Oct. 1992

Analytical Modeling of SH-2F Helicopter Shipboard Operation

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An analysis of the shipboard characteristics of the SH-2F helicopter in response to prescribed deck motion, deck friction, and steady wind conditions has been developed. The objective of deriving the SH-2F shipboard dynamic model is to define safe conditions for launching and recovering the helicopter from the flight deck of U.S. Navy frigates and destroyers. Operational conditions of interest include helicopter and ship deck dynamic interactions that could potentially cause dangerous interference between the helicopter and the ship, such as sliding or tipping of the helicopter. The wind condition, ship deck motion, helicopter rotor thrust, and friction coefficients between helicopter tires and flight-deck surfaces are found to be important parameters that affect the helicopter shipboard operations. Four sets of aerodynamic characteristics are modeled in the analysis: one with the rotor operating; one with the rotor stopped and inoperative; one with rotor folded; and one for the fuselage. The ship motion data, including three linear translation and two angular rotation degrees of freedom (roll and pitch) are described in the time domain. The equations of motion of the shipboard dynamic model are derived using the energy method.

I. Introduction

An analysis of the shipboard characteristics of the SH-2F helicopter (shown in Fig. 1) in response to prescribed deck motion, deck friction, and steady wind conditions has been developed and analyzed. Over 200 SH-2F helicopters have been deployed aboard U.S. Navy frigates and destroyers. Having a shipboard dynamic analytical model and a trained PC operator onboard the ships to obtain a safe flight envelope under adverse sea conditions are essential because SH-2F helicopters will remain in combat missions until the year 2010.

A sea trial involving an SH-2F helicopter and a DE-1052-class ship was conducted in 1974 and reported in Ref. 1. The report concerns two different types of analyses of ship motion, including the standard power spectrum analysis of ship motions and the aircraft event analysis of ship motions during the specific time interval of an aircraft event. Both types of analyses are required in order to relate ship motions to the degree of difficulty encountered in such events.

Sea trial results that deal with the direct operation of the aircraft have been documented in Ref. 2. A generalized ship motion database applicable to a set of five ships was developed in Refs. 3 and 4. The database consists of an extensive frequency domain database and a time domain database selected from the frequency domain results. The time history database provides a rational, comprehensive, and controlled set of ship motion data to drive various physical or mathematical ship simulations.

The operation of the SH-2F helicopter from the decks of small ships was also simulated using a large amplitude motion simulator reported in Ref. 5. It describes the simulation facility and the mathematical programs. The results show the simulator to be a useful tool in simulating the ship-landing problem.

In Ref. 6, a computer program was developed to predict helicopter landing and arresting system loads and deflections for the SH-60B operating on ships equipped with the recovery assist, securing, and traversing (RAST) system. The computational capability is restricted to on-deck operations where the loading environment is associated with the dynamic responses of the ship in a given sea state. The helicopter rotor aerodynamic forces and moments do not include steady wind effect. The main rotor lift generated by the rotor is assumed to be 25% of helicopter total gross weight. A static solution is obtained based on an iteration procedure.

In Ref. 7, the mathematical models were presented for a baseline visual landing aids suite, two versions of the airwake and the ship motions. Existing operational procedures for launch and recovery of helicopters on small aviation facility ships were used as a baseline for quantifying the models. The

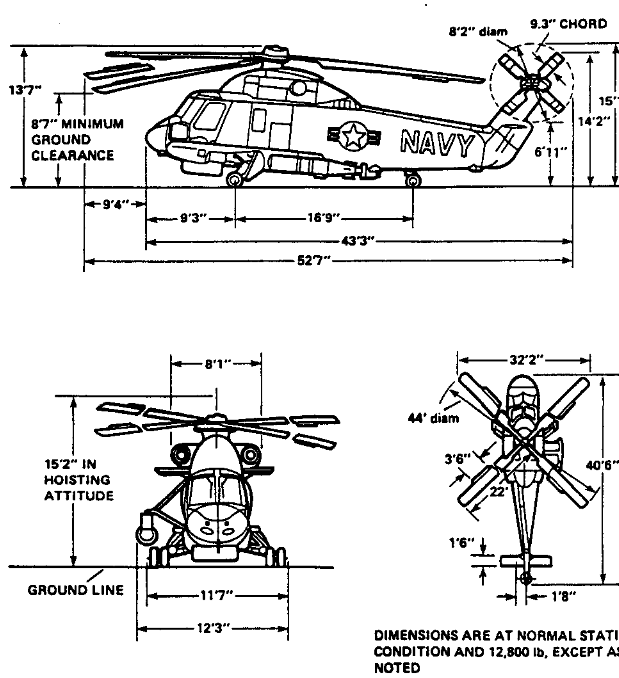

Fig. 1 Kaman SH-2F helicopter.

Received July 6, 1991; revision received Oct. 5, 1991; accepted for publication Oct. 7, 1991.

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baseline visual landing aids suite is the current DD 963 visual landing aids complement, plus the minioptical landing system.

For SH-2F helicopters flown with −101 rotors or composite main rotor blades (CMRB), the correlation between test data and analyses are shown in Refs. 8 and 9. Good correlation between tests and analyses has been successfully developed. These correlations improve the helicopter analytical model used in the shipboard operation program. Vibration reduction analyses on the SH-2F helicopter equipped with a −101 rotor using higher harmonic control inputs are also presented in Ref. 10.

For this paper, the QuickBasic language developed by Microsoft Company was used on an IBM personal computer to solve the equations that predict the SH-2F helicopter center of gravity responses due to ship deck motion. The SH-2F helicopter is represented with the rotor turning, stopped, and folded in order to simulate all possible combinations of the helicopter operation on the flight deck as shown in Refs. 11 and 12. Operational conditions of interest include helicopter and ship deck dynamic interactions that would cause helicopter sliding or lifting one main wheel off the ship deck. Three translational and three rotational degrees of freedom of the helicopter c.g. motions are modeled to predict the helicopter responses due to the excitation. All coordinate systems defined on the helicopter and the ship locations are using right hand rule, which has longitudinal axis positive forward, lateral axis positive to the left, and vertical axis positive upward.

The aerodynamic forces and moments generated by the SH-2F helicopter rotor and fuselage due to wind speeds are also computed. For rotor operating cases, a set of equations in the wind axis system is used to determine the proper aerodynamics. The orientation of the wind axis system with respect to the ship is accomplished by axes transformations. Three sets of aerodynamic characteristics other than the operating rotor cases are described in the aerodynamic tables. These aerodynamic tables are given as functions of the wind azimuth angles with respect to the helicopter longitudinal axis.

The equations of motion are solved in the quasisteady fashion in less than one-third of a second refresher rate to the prescribed deck motion time histories. This quick response solution characteristic can be used to run the program in a real-time manner to obtain the safe flight envelope when interfaced with the ship motion data.

II. Technical Analysis

A. Analytical Assumptions

There are several assumptions used in the analysis to obtain the equations of motion of the ship and aircraft interaction due to ship deck motion and steady wind conditions. These assumptions should be carefully considered when interpreting and determining the helicopter reaction loads and motions. The assumptions are as follows.

1) A rigid body helicopter fuselage is assumed in the analysis.

2) The equations of motion of the helicopter with respect to the ship are linearized based on small angle assumptions. Ship motion, helicopter orientation on the flight deck, and wind direction are considered large angles.

3) The helicopter landing-gear spring rates and damping are assumed linear.

4) All aerodynamic tables are determined as a function of the steady wind angle with respect to the longitudinal axis of the helicopter when the ship is at the level position.

5) The natural frequencies introduced by the helicopter landing-gear spring rates are assumed much higher than the ship motion natural frequencies; therefore, the helicopter natural frequencies will not be affected by the ship deck motion.

6) The steady wind speed and direction and ship motion data are assumed unchanged during a one-third second interval.

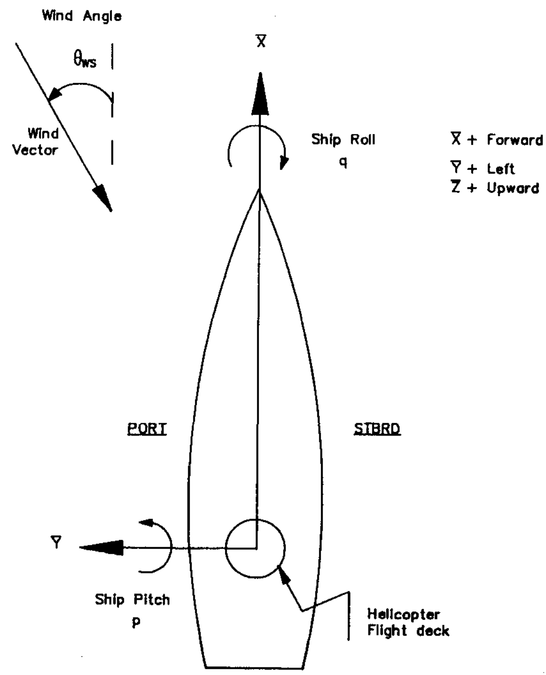

Fig. 2 Ship coordinate system for ship motion parameters and relative wind angle.

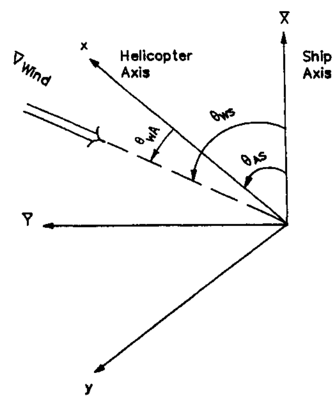

Fig. 3 Wind angle relationship between ship and helicopter.

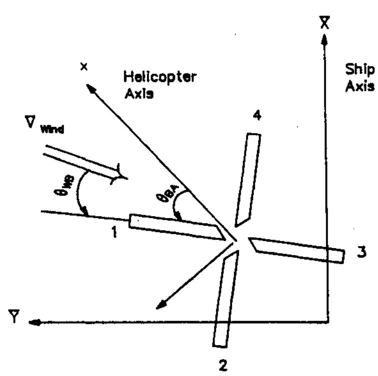

Fig. 4 Relationship between ship and helicopter wind angle for rotor inoperative.

B. Ship Motion Data

Ship motion data due to the sea wave and the steady wind conditions are defined in the ship coordinate system (Fig. 2). These data include relative speed and direction, and also include three linear accelerations $\ddot{X}$, $\ddot{Y}$, $\ddot{Z}$, two angular displacements q, p, two angular velocities $\dot{q}$, $\dot{p}$, and two angular accelerations $\ddot{q}$, $\ddot{p}$ of the ship motions. All the data are given in the time domain. Ship motions are measured on the centerline of the ship deck directly under the landing platform.

Table 1 Helo landing gear friction coefficient effect, no wind, θ_{AS} = 0, 12,800 lb gw

Friction coefficient between helo landing gear and ship deck		0.7[a]	0.5[b]	0.3[c]	0.15[d]
Helo slides on ship deck	Ship roll angle, deg	26	19	12	6.0
	Helo roll angle, deg	4.8	3.8	2.4	1.2
	Right wheel force, lb	8157	7862	7009	6075
	Left wheel force, lb	326	1641	3149	4086
	Tail wheel force, lb	2207	2473	2644	2645
Helo wheel lifts off ship deck	Ship roll angle, deg	31	31	31	31
	Helo roll angle, deg	5.9	5.9	5.9	5.9
	Right wheel force, lb	9412	9412	9412	9412
	Left wheel force, lb	0	0	0	0
	Tail wheel force, lb	2376	2376	2376	2376

[a]Dry flight deck.
[b]Worn flight deck.
[c]Wet flight deck.
[d]Oily flight deck.

The instrumentation station is equipped to measure pitch, roll, yaw of ship course, and accelerations in the vertical, lateral, and longitudinal directions. Yaw degree of freedom of the ship motion is not used in the analysis. Ship speed and course are taken by means of repeaters from the ship's own sensors. Ship angular velocities and accelerations are obtained by differentiating the angular displacement with respect to time, once and twice, respectively. Every one-third second new wind condition and ship motion data will be given as the inputs to the computer program.

C. Helicopter Aerodynamic Characteristics

1. Aerodynamic Tables Setup

The aerodynamic forces and moments on the helicopter rotor and fuselage due to steady wind conditions are determined. The rotor operating is given as a series of equations in the wind axis system shown in Ref. 11. The three forces and moments are given as derivatives with respect to rotor angle of attack and pitch rate.

Three different aerodynamic tables for fuselage and nonoperating rotor conditions are used for tables look-up as a function of wind azimuth angles. These aerodynamic tables are 1) one table for the rotor stopped, but extended; 2) one table for the rotor folded; and 3) one table for the fuselage.

2. Relative Wind Angle

The relationship between relative ship and helicopter wind angles is shown in Figs. 3 and 4. The relative ship wind angle θ_{ws} with respect to ship longitudinal axis is obtained from ship motion data. The helicopter operating onboard the ship flight deck is not coincident with the ship axes. In normal operation on the landing platform, there is an angle between the helicopter and the ship longitudinal axes θ_{As}. Therefore, the relative wind angle θ_{wA} with respect to helicopter longitudinal axis is the difference between the relative wind angle with respect to ship axis minus the helicopter longitudinal axis with respect to ship axis, as shown in Fig. 3. θ_{wA} is the angle used to compute or to look up the aerodynamic characteristics for 1) rotor turning in operation, 2) rotor folded, and 3) helicopter fuselage aerodynamics.

For rotor extended/inoperative, additional information is required to define fully the relative wind angle between the wind axis and the pitch axis of the rotor blades, shown in Fig. 4. The blade angle with respect to helicopter longitudinal axis

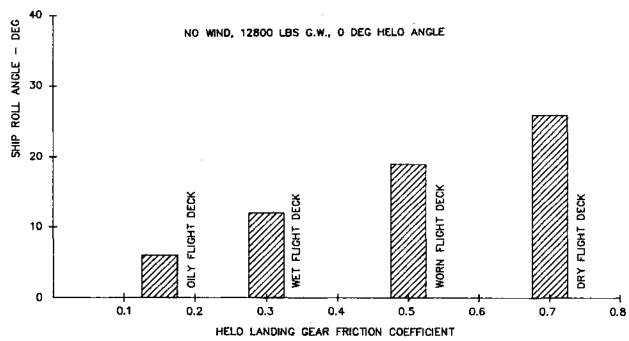

Fig. 5 Helo landing gear friction coefficient effect at helo slides on ship deck.

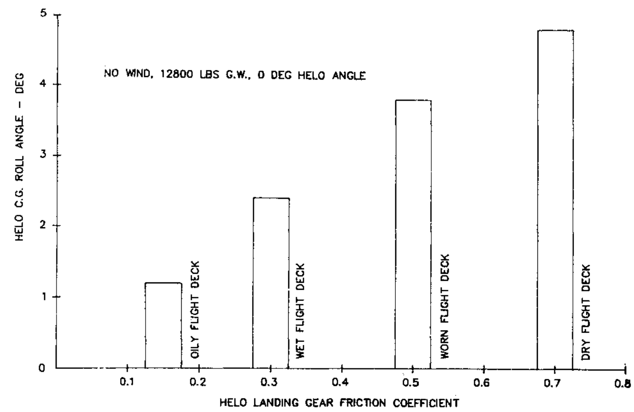

Fig. 6 Helo c.g. roll angle vs landing gear friction coefficient at helo slides on ship deck.

θ_{BA} is needed when the blades are stopped at any angle other than straight into the helicopter longitudinal axis. The wind angle with respect to helicopter rotor blade no. 1 is defined as follows:

$$\theta_{wB} = \theta_{wA} - \theta_{BA} \tag{1}$$

θ_{wB} is used to find the rotor aerodynamics from the aerodynamic table when the rotor is extended at any azimuth without turning.

III. SH-2F Landing Gear

The SH-2F helicopter has two retractable main landing gears, each with dual wheels, located in the forward fuselage and one, full-swivel, nonretractable tail gear located in the aft fuselage. The tail wheel can be swiveled through 360 deg and locked in the fore and aft positions. The main landing gears are designed to have relatively larger left and right wheel span suitable for operating from smaller classes of U.S. Navy ships. The spring rates and damping characteristics of the landing gear are obtained from various tests conducted in the development of the high energy absorption landing gear. Nonlinear landing gear spring rate effects are neglected in the first phase of the analysis.

IV. Equations of Motion

The equations of motion of the shipboard dynamic model are derived about the helicopter c.g. using the energy method. The position vectors of the points of interest on the helicopter are first defined with respect to helicopter c.g. without the ship motion. Then, the ship motion effects are added in the kinetic energy terms of the equations to represent the actual responses of the system. The helicopter landing gear spring terms are not changed by the ship motions because the landing gear spring deflections are defined with respect to the ship deck. All the aerodynamics generated by the rotor and fuselage due to steady wind conditions are transformed into the helicopter c.g. location. Also, the helicopter gravitational force effects are added on the right-hand side of the equations due to ship deck motion. Quasisteady solution technique is used to find the response of the system due to ship motion. The computational time used to find the solution is within one-third of a second using the QuickBasic language.

V. Numerical Results

The friction coefficients between the SH-2F helicopter and the ship flight-deck surfaces are important parameters that affect the helicopter shipboard operation. The variation of friction coefficients between wet, oily, and worn deck conditions changes up to a factor of five from the dry deck condition. Table 1 presents the numerical results for SH-2F helicopter and ship flight-deck surface friction coefficient effects due to ship rolling motion. Ship rolling angles that would cause a helicopter to slide or tip-off dangerously on the flight deck are presented. Helicopter c.g. rolling angle and landing gear reaction forces are also listed at the helicopter sliding on or tipping off the flight-deck condition. All numerical results listed in Table 1 are plotted and shown in Figs. 5–7.

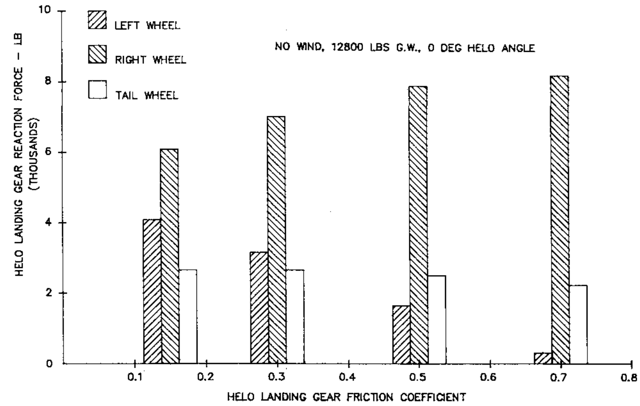

Fig. 7 Helo landing gear reaction forces vs helo landing gear friction coefficient at helo slides on ship deck.

In the no-wind situation and no relative ship speed, the helicopter starts to slide on the dry deck $\mu = 0.7$ when the ship rolls more than 26 deg, with typical helicopter mission gross weight at 12,800 lbs and with both helicopter and ship coordinate axes coincident. Under this condition, the helicopter c.g. rolls 4.8 deg with respect to ship deck motion. Also, the helicopter's right, left, and tail landing wheel reaction forces are 8157, 326, and 2207 lb, respectively. The helicopter also lifts one main wheel off the flight deck when the ship rolls more than 31 deg. Under this condition, the helicopter c.g. rolls 5.9 deg with respect to ship deck motion. The helicopter's right, left, and tail wheel forces are 9412, 0, and 2373 lb, respectively. In the worst condition, when the ship flight deck becomes oily $\mu = 0.15$, the helicopter starts sliding when the ship rolls more than 6.0 deg. The helicopter c.g. has only 1.2 deg roll angle with respect to ship deck motion and the helicopter's right, left, and tail landing wheel forces are 6075, 4086, and 2645 lb, respectively. Numerical results indicate that good and well-maintained ship flight decks can have 20 deg more roll angle before causing the helicopter to slide on the deck, as compared to an oily deck.

Table 2 presents the numerical results of crosswind effects on helicopter shipboard operation when the helicopter rotor is turning, sitting on an old and worn flight deck $\mu = 0.5$, with longitudinal axis straight into the ship axis. Under 45 kt crosswind condition, the helicopter starts to slide on the flight deck when the ship rolls more than 13 deg, 6 deg sooner than the no-wind situation. The helicopter c.g. has 2.5 deg roll angle with respect to ship deck motion. The helicopter c.g.

Table 2 Crosswind speed effect, $\theta_{AS} = 0$; 12,800 lb gw; rotor turning; wind angle = 90 deg; $\mu = 0.5$

Wind speed with respect to ship (kts)		0	15	30	45
Helo slides on ship deck	Ship roll angle, deg	19	18.5	17.5	13
	Helo roll angle, deg	3.8	3.5	2.7	2.5
	Right wheel force, lb	7862	7156	6066	5586
	Left wheel force, lb	1641	1496	1690	1454
	Tail wheel force, lb	2473	2337	2286	2322
Helo wheel lifts off ship deck	Ship roll angle, deg	31	26	25	24
	Helo roll angle, deg	5.9	4.4	4.0	2.8
	Right wheel force, lb	9412	6991	6084	4342
	Left wheel force, lb	0	0	0	0
	Tail wheel force, lb	2376	1865	1799	1744

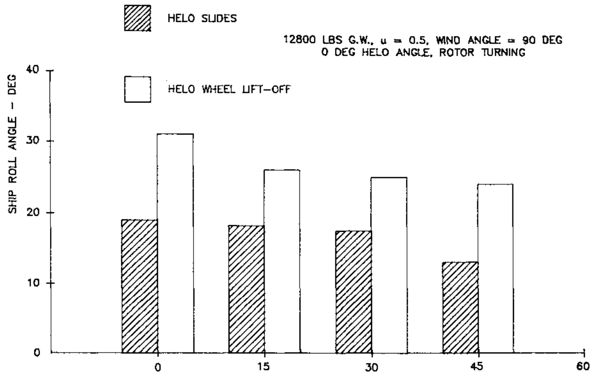

Fig. 8 Ship roll angle vs crosswind speed.

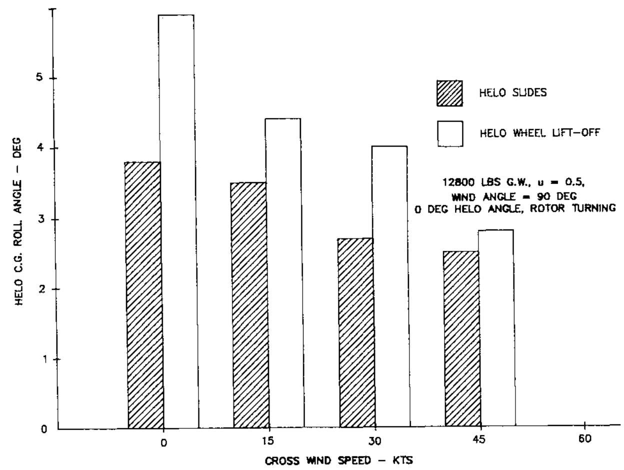

Fig. 9 Helo c.g. roll angle vs crosswind speed.

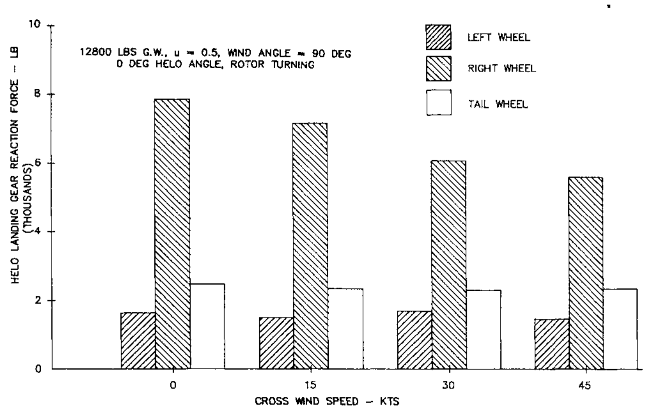

Fig. 10 Helo landing gear reaction forces vs crosswind speed at helo slides on ship deck.

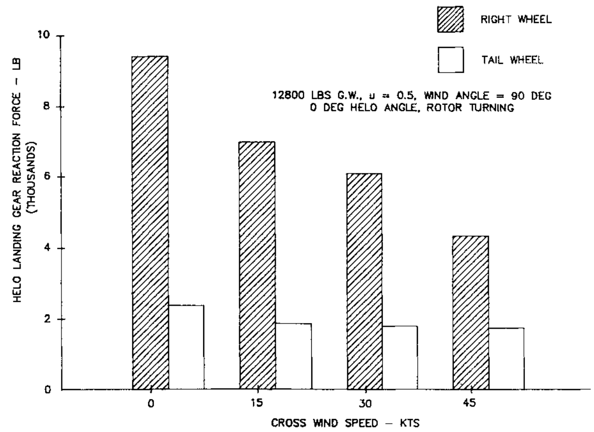

Fig. 11 Helo landing gear reaction forces vs crosswind speed at helo wheel lift-off.

rolls 1.3 deg less than no-wind condition. The helicopter landing gear generates smaller reaction forces under 45 kt wind conditions as compared to the calm wind condition. Also, under 45 kt crosswind condition, the helicopter starts to tip one wheel off the deck when the ship rolls more than 24 deg, which is 7 deg sooner than the no-wind condition. The helicopter c.g. has 2.8 deg roll angle with respect to ship deck motion under this wind condition. Also, the helicopter c.g. rolls 3.1 deg less than no-wind condition. Because the helicopter rotor blades generate lift under the crosswind condition when the ship rolls about its longitudinal axis, this lift force will reduce total helicopter weight exerted on the flight deck and cause the helicopter landing gear to slide or tip-off sooner than in the no-wind condition. Also, the drag force generated by the fuselage will push the helicopter into sliding along the wind direction due to the crosswind. For a 30 kt crosswind condition, the helicopter slides when the ship's rolling angle is more than 17.5 deg, 1.5 deg sooner than the no-wind situation, and lifts one main wheel off the deck when the ship rolls more than 25 deg, 6 deg sooner than the no-wind condition. Numerical results listed in Table 2 are plotted and shown in Figs. 8–11.

Table 3 presents the numerical results for wind angle effects on SH-2F helicopter shipboard operation with both helicopter and ship longitudinal axes coincident with each other. The wind direction is measured with respect to the ship coordinate system. For a wind speed of 30 kt and a flight-deck friction coefficient of $\mu = 0.5$, the helicopter starts to slide when the ship's rolling angle reaches 19 deg under the head wind condition. This roll angle gives 1.5 deg more than the value obtained from the crosswind condition. Under the head wind condition, the helicopter starts to lift one main wheel off the deck when the ship's rolling angle reaches 27 deg, 2 deg higher than the crosswind condition.

For a 30 kt wind with a 45 deg wind angle condition, analysis indicates that the helicopter slides on the deck above an 18 deg ship roll angle. This roll angle gives 0.5 deg higher than the crosswind condition. Similarly, the helicopter lifts one main wheel off the deck above a 26 deg ship roll angle, which is 1 deg higher than the baseline crosswind value.

Table 4 presents the numerical results of the helicopter and ship relative angle effects on the SH-2F helicopter shipboard operation when the helicopter rotor is turning at the 30 kt crosswind condition. The helicopter operating onboard the ship flight deck is not necessarily coincident with the ship axes. In normal operation on the landing platform, there is an angle between helicopter and ship longitudinal axes.

For the helicopter longitudinal axis having 45 deg, with respect to the ship longitudinal axis, the helicopter slides on the flight deck as the ship angle rolls above 22 deg, 4.5 deg higher than the value obtained at 0 deg between the helicopter and ship axes. This is because the cosine effect of the ship roll angle applied on the helicopter longitudinal axis has a stabilizing effect on the helicopter shipboard operation.

Also, for the 45 deg helicopter and ship angle condition, the helicopter starts to tip-off on the flight deck as the ship roll angle reaches 31 deg, 6 deg higher than 0 deg helicopter and ship relative angle condition. With this information, the shipboard officer can give the best order for ship speed and course to avoid dangerous shipboard operation under adverse sea conditions.

Table 5 presents the numerical results of ship lateral acceleration effects on helicopter operation on ships. Ship lateral acceleration, obtained from ship motion data, was treated as a forcing function in the analysis applied on the right-hand side of the equations of motion and can be a very important factor for helicopter on-deck operations. Ship motion data

Table 3 Wind angle effect, θ_{AS} = 0; 12,800 lb gw; rotor turning; wind speed = 30 kts; μ = 0.5

Wind angle with respect to ship (deg)		0	30	45	60	90
Helo slides on ship deck	Ship roll angle, deg	19	19	18	18	17.5
	Helo roll angle, deg	3.7	3.5	3.0	2.9	2.7
	Right wheel force, lb	7909	7043	6649	6345	6066
	Left wheel force, lb	1798	1324	1796	1644	1690
	Tail wheel force, lb	2591	2317	2382	2301	2286
Helo wheel lifts off ship deck	Ship roll angle, deg	27	26	26	25	25
	Helo roll angle, deg	4.5	4.3	4.0	3.9	4.0
	Right wheel force, lb	7671	6959	6331	6368	6084
	Left wheel force, lb	0	0	0	0	0
	Tail wheel force, lb	2089	1851	1689	1813	1799

Table 4 Angle between helo and ship effect, 12,800 lb gw; rotor turning; wind speed = 30 kts; wind angle = 90 deg; μ = 0.5

Angle between helo and ship (deg)		0	30	45
Helo slides on ship deck	Ship roll angle, deg	17.5	18	22
	Helo roll angle, deg	2.7	2.3	1.9
	Right wheel force, lb	6066	5265	4224
	Left wheel force, lb	1690	1475	1181
	Tail wheel force, lb	2286	2754	2893
Helo wheel lifts off ship deck	Ship roll angle, deg	25	27	31
	Helo roll angle, deg	4.0	2.7	2.2
	Right wheel force, lb	6084	4429	3250
	Left wheel force, lb	0	0	0
	Tail wheel force, lb	1799	2781	2717

Table 5 Ship lateral acceleration effect, θ_{AS} = 0; 12,800 lb gw; rotor turning; wind speed = 30 kts; wind angle = 90 deg; μ = 0.5

Ship lateral acceleration, g		0	0.1	0.2	0.3
Helo slides on ship deck	Ship roll angle, deg	17.5	12.0	7.0	3
	Helo roll angle, deg	2.7	2.1	1.2	0.3
	Right wheel force, lb	6066	6029	5611	5336
	Left wheel force, lb	1690	2629	3694	4827
	Tail wheel force, lb	2286	2477	2605	2797
Helo wheel lifts off ship deck	Ship roll angle, deg	25	25	25	26
	Helo roll angle, deg	4.0	3.7	3.5	3.1
	Right wheel force, lb	6084	5864	5643	4972
	Left wheel force, lb	0	0	0	0
	Tail wheel force, lb	1799	1797	1796	1611

obtained from Ref. 1 during a 4-day sea trial indicated that the maximum range of the ship lateral acceleration, 0.3 g, is enough to simulate most of the sea-states encountered. Numerical results shown in Table 5 are plotted in Figs. 12–15.

For a ship having 0.2 g lateral acceleration, the helicopter starts to slide on the flight deck as the ship's angle rolls more than 7 deg, 10.5 deg less than no lateral acceleration condition. The helicopter c.g. has 1.2 deg roll angle with respect to ship deck motion and the helicopter's right, left, and tail landing wheel reaction forces are 5611, 3694, and 2605 lb, respectively. Numerical results also indicate that ship lateral acceleration has little effect on helicopter tip-off one main wheel on the flight deck condition. Under this condition, the helicopter c.g. has 3.5 deg roll angle and the helicopter's right and tail landing wheels have 5643 and 1796 lb reaction forces, respectively.

For a ship having 0.3 g lateral acceleration, the helicopter starts to slide on the flight deck when the ship's angle rolls more than 3 deg, 14.5 deg less than no lateral acceleration condition. Analysis proves that ship lateral acceleration is an extremely critical parameter for helicopter shipboard operation. Extra care must be implemented to operate a helicopter on the flight deck if the ship has lateral acceleration more than 0.3 g.

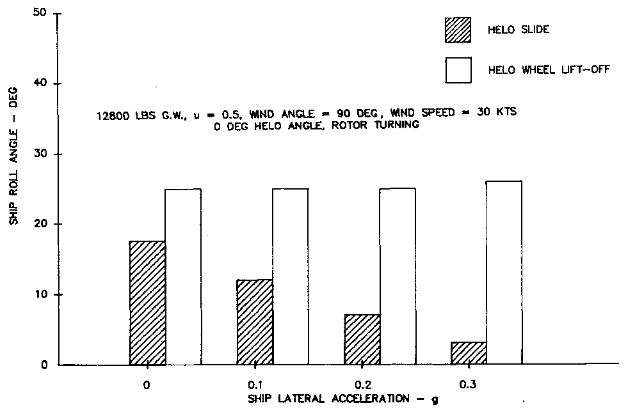

Fig. 12 Ship roll angle vs ship lateral acceleration.

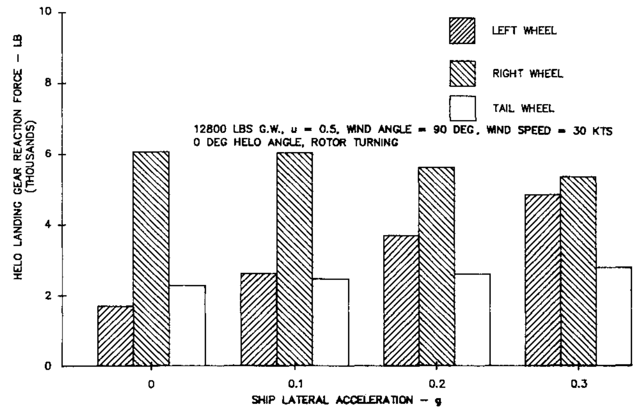

Fig. 14 Helo landing gear reaction forces vs ship lateral acceleration.

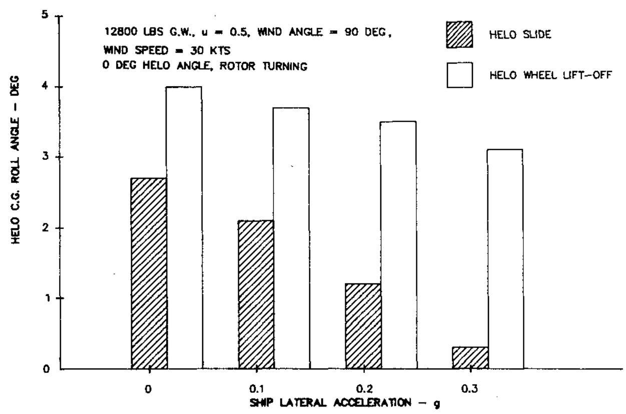

Fig. 13 Helo c.g. roll angle vs ship lateral acceleration.

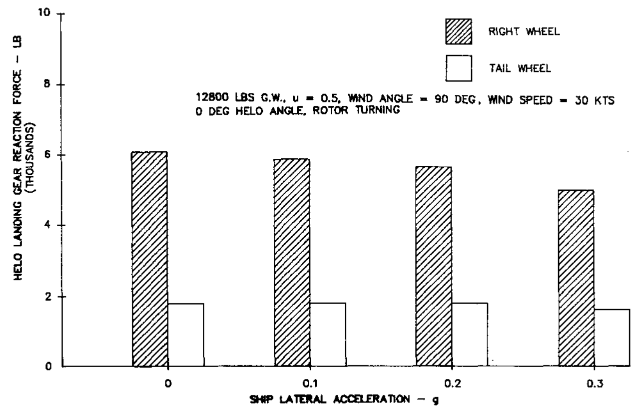

Fig. 15 Helo landing gear reaction forces vs ship lateral acceleration.

Table 6 Ship vertical acceleration effect, θ_{AS} = 0; 12,800 lb gw; rotor turning; wind speed = 30 kts; wind angle = 90 deg; μ = 0.5

Ship vertical acceleration, g		0	−0.1	−0.2	−0.3
Helo slides on ship deck	Ship roll angle, deg	17.5	13.0	12.0	12.0
	Helo roll angle, deg	2.7	2.5	2.3	2.3
	Right wheel force, lb	6066	5565	5236	4729
	Left wheel force, lb	1690	1490	1416	908
	Tail wheel force, lb	2286	2067	1954	1689
Helo wheel lifts off ship deck	Ship roll angle, deg	25	24	19	18
	Helo roll angle, deg	4.0	3.5	3.3	3.0
	Right wheel force, lb	6084	5507	5102	4684
	Left wheel force, lb	0	0	0	0
	Tail wheel force, lb	1799	1709	1539	1449

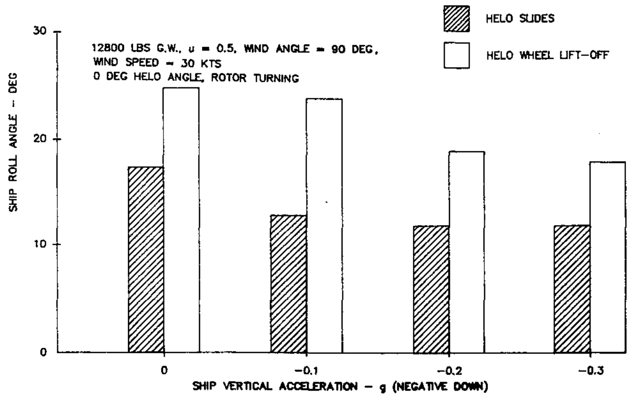

Fig. 16 Ship roll angle vs ship vertical acceleration.

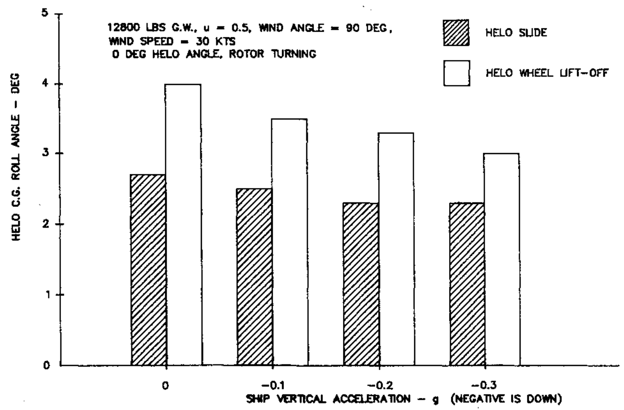

Fig. 17 Helo c.g roll angle vs ship vertical acceleration.

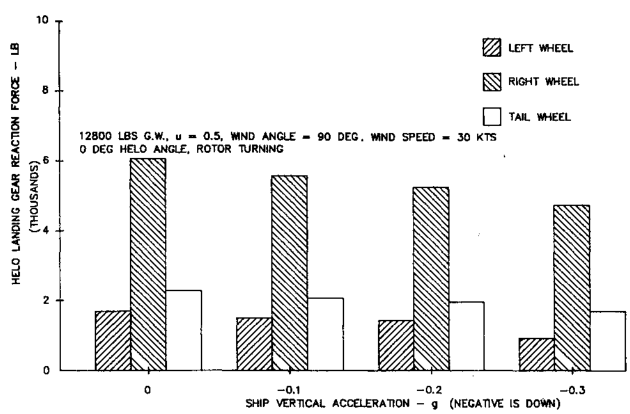

Fig. 18 Helo landing gear reaction forces vs ship vertical acceleration at Helo slides on ship deck.

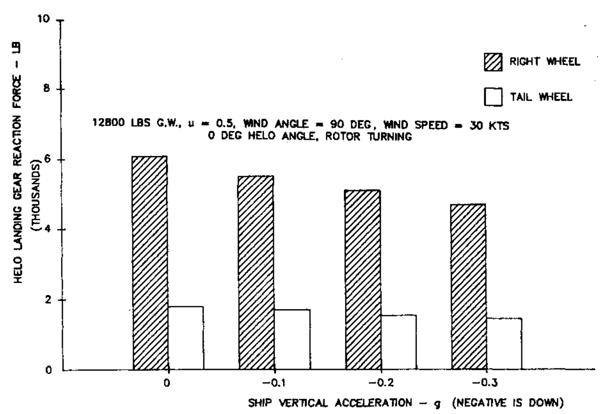

Fig. 19 Helo landing gear reaction force vs ship vertical acceleration at helo wheel lift-off.

The numerical results for ship vertical acceleration effects on helicopter on-deck operation are presented in Table 6 and Figs. 16–19, with both helicopter and ship longitudinal axes coincident. Under 30 kt crosswind and ship flight-deck friction coefficient of $\mu = 0.5$ condition, the helicopter starts to slide on the flight deck as the ship angle rolls more than 13 deg with $-0.1\ g$ ship vertical acceleration and 12 deg with $-0.2\ g$ ship vertical acceleration, respectively. These ship roll angles have at least 4.5 deg less than the value obtained from no ship vertical acceleration condition. The helicopter c.g. has 2.3 deg roll angle in addition to ship deck motion. The helicopter landing wheel reaction forces for right, left, and tail wheels are 5236, 1416, and 1954 lb, respectively. For a ship having $-0.2\ g$ vertical acceleration, the helicopter starts to tip-off the flight deck as the ship attains a roll angle more than 19 deg, 6 deg less than zero ship vertical acceleration condition. Under this condition, the helicopter c.g. has 3.3 deg roll angle. The right landing wheel has 5102 lb reaction force and the tail wheel has 1539 lb reaction force. (Other numerical data can be found in Ref. 11.)

VI. Conclusions

Based on technical analysis and numerical results, the analytical modeling of SH-2F helicopter shipboard operation has been successfully developed. The conclusions obtained from these numeric results are as follows:

1) The friction coefficients between SH-2F helicopter and ship flight deck that changed up to a factor of five from the dry deck to wet and oily deck conditions are found to be important parameters, which would cause the helicopter to slide-on or tip-off the flight deck.

2) The helicopter rotor lift will reduce total weight on the landing gear; therefore, causing the helicopter slide-on or tip-off the flight deck sooner than the no lift condition.

3) Based on numerical data shown in Tables 1–6, the best wind speed, relative wind angle, and helicopter and ship angle can stabilize helicopter shipboard operation under adverse sea conditions.

4) Ship lateral acceleration is the most important factor to cause helicopter slide on the flight deck. For a ship having 0.3 g or more lateral acceleration, the helicopter will slide on the flight deck as the ship rolls more than 3 deg.

5) For a ship having more than $-0.1\ g$ vertical acceleration, there is an increasing trend of difficulty to operate a helicopter on board a ship.

6) Further study and tests are required to verify the analytical model.

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